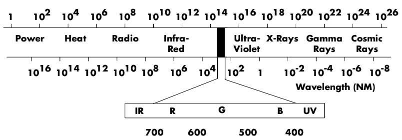
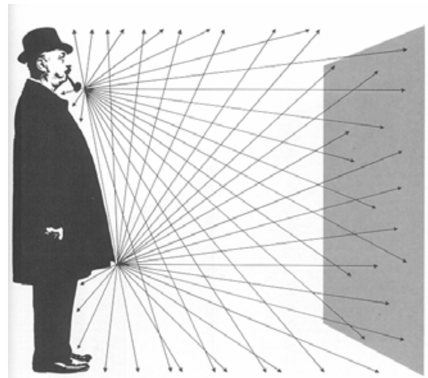
Light

Visible electromagnetic radiation

Power spectrum





From London and Upton

Polarization

Photon (quantum effects)

Wave (interference, diffraction)

Topics

Light sources and illumination

Radiometry and photometry

Quantify spatial energy distribution

- Radiant intensity
- Irradiance
  - Inverse square law and cosine law
- Radiance
- Radiant exitance (radiosity)

Illumination calculations

- Irradiance from environment

Radiometry and Photometry

Radiant Energy and Power

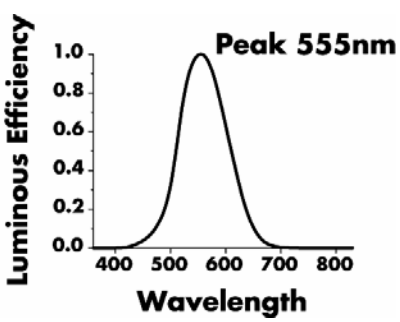
Power: Watts vs. Lumens

Φ

- Energy efficiency
- Spectral efficacy

Energy: Joules vs. Talbot

- Exposure
  - Film response
  - Skin - sunburn



Luminance

$$Y = \int V(\lambda) L(\lambda) d\lambda$$

Radiometry vs. Photometry

Radiometry [Units = Watts]

- Physical measurement of electromagnetic energy

Photometry and Colorimetry [Lumen]

- Sensation as a function of wavelength
- Relative perceptual measurement

$B = Y^{1/3}$

Brightness [Brils]

- Sensation at different brightness levels
- Absolute perceptual measurement
- Obeys Steven's Power Law

Blackbody Radiation

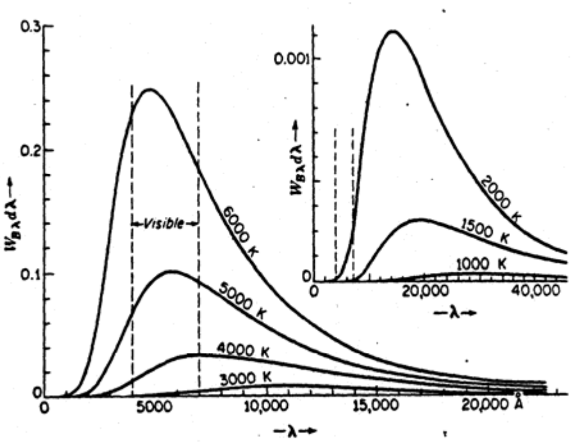


FIGURE 21F
Blackbody radiation curves plotted to scale. Ordinates give the energy in calories per square centimeter per second in a wavelength interval $d\lambda$ of 1 Å. For numerical values, see "Smithsonian Physical Tables," 8th ed., p. 314.

Tungsten Lamp

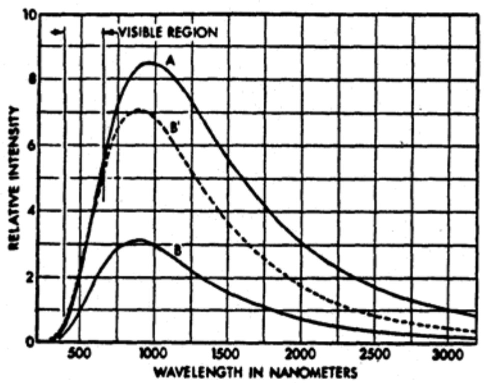
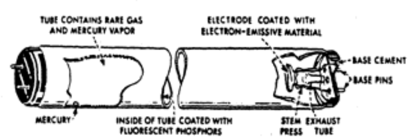


Fig. 8–1. Radiating characteristics of tungsten. Curve A: radiant flux from one square centimeter of a blackbody at 3000 K. Curve B: radiant flux from one square centimeter of tungsten at 3000 K. Curve B′: radiant flux from 2.27 square centimeters of tungsten at 3000 K (equal to curve A in visible region). (The 500-watt 120-volt general service lamp operates at about 3000 K.)

Fluorescent Bulb



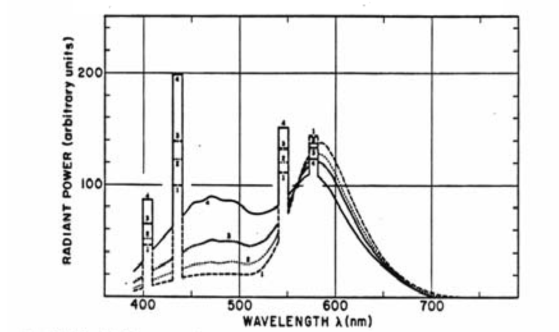


Fig. 3(1.2.3). Relative spectral radiant power distributions of common fluorescent lamps: (1) standard warm white; (2) white; (3) standard cool white; and (4) daylight. The distribution curves have been scaled by appropriate constant factors to provide a common value of 100 at $\lambda = 560$ nm.

Sunlight

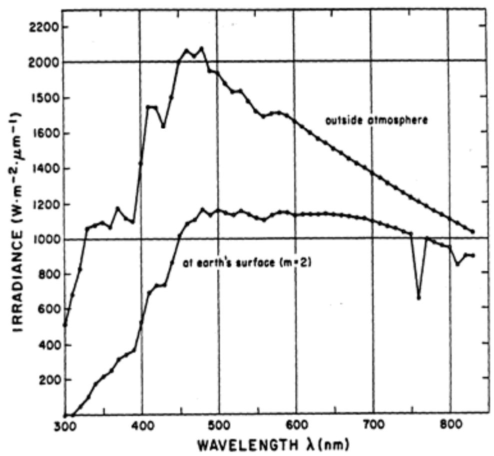
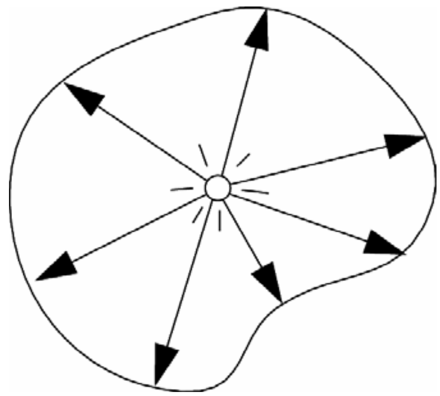


Fig. 1(1.2.1). NASA standard data of spectral irradiance ($W \cdot m^{-2} \cdot \mu m^{-1}$) for the solar disk measured outside the atmosphere (solid dots) and at the earth's surface at air mass 2 (open circles). Data points are those given in Table 1(1.2.1). Neighboring data points have been connected by straight lines for illustrative purposes only.

Radiant Intensity

Radiant Intensity

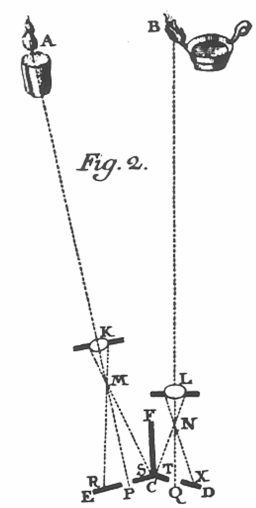
Definition: The *radiant* (*luminous*) *intensity* is the power per unit solid angle emanating from a point source.



$$I(\omega) \equiv \frac{d\Phi}{d\omega}$$

$$\left[\frac{W}{sr}\right]\left[\frac{lm}{sr} = cd = candela\right]$$

The Invention of Photometry



Bouguer's classic experiment

- Compare a light source and a candle
- Move until they both appear equally bright
- Intensity is proportional to ratio of distances squared

Definition of a candela

- Originally a "standard" candle
- Currently 550 nm laser w/ 1/683 W/sr
- 1 of 6 fundamental SI units

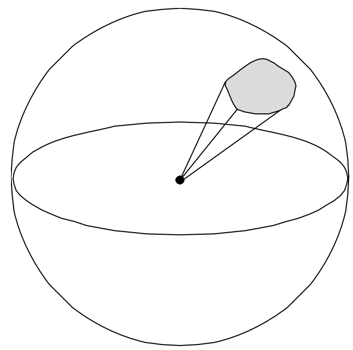
Angles and Solid Angles

- **Angle** $\theta = \frac{l}{r}$

  $\Rightarrow$ **circle has 2π radians**

- **Solid angle** $\Omega = \frac{A}{R^2}$

  $\Rightarrow$ **sphere has 4π steradians**



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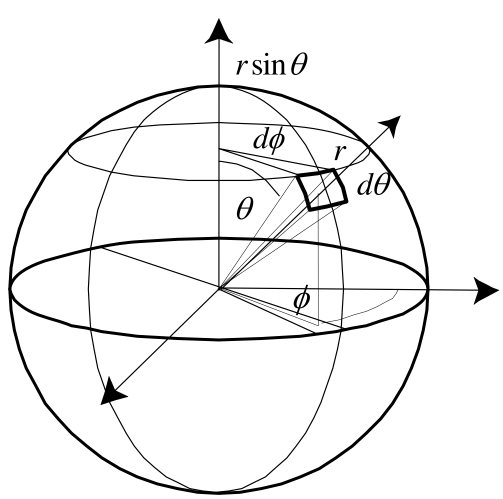
Differential Solid Angles



$$dA = (r\,d\theta)(r\sin\theta\,d\phi)$$
$$= r^2 \sin\theta\,d\theta\,d\phi$$

$$d\omega = \frac{dA}{r^2} = \sin\theta\,d\theta\,d\phi$$

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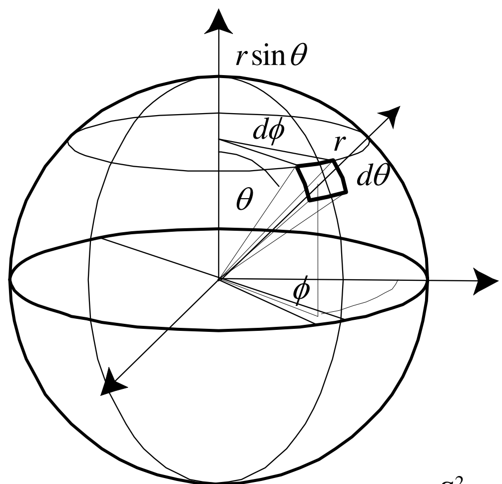
Differential Solid Angles



$$d \quad \sin \quad d \quad d$$

$$\Omega = \int_{S^2} d\omega$$

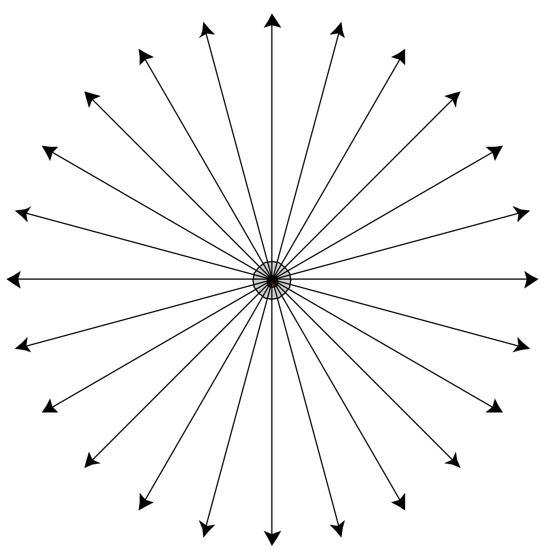
$$= \int_0^{\pi}\int_0^{2\pi} \sin\theta \, d\theta \, d\phi$$

$$= \int_{-1}^{1}\int_0^{2\pi} d\cos\theta \; d\phi$$

$$= 4\pi$$

Sphere S^2

Isotropic Point Source

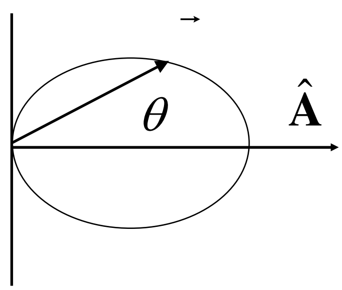


$$\Phi = \int_{S^2} I \, d\omega$$

$$= 4\pi I$$

$$I = \frac{\Phi}{4\pi}$$

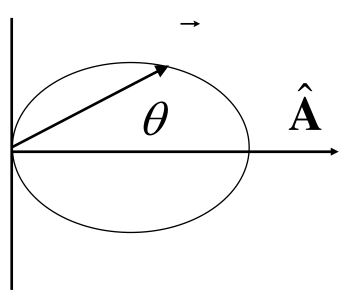
Warn's Spotlight



$$I(\ )\quad \cos^s \qquad (\vec{\ }\ \ \hat{\mathbf{A}})^s$$

$$\Phi = \int_0^{2\pi}\int_0^1 I(\omega)\, d\cos\theta\, d\varphi$$

Warn's Spotlight

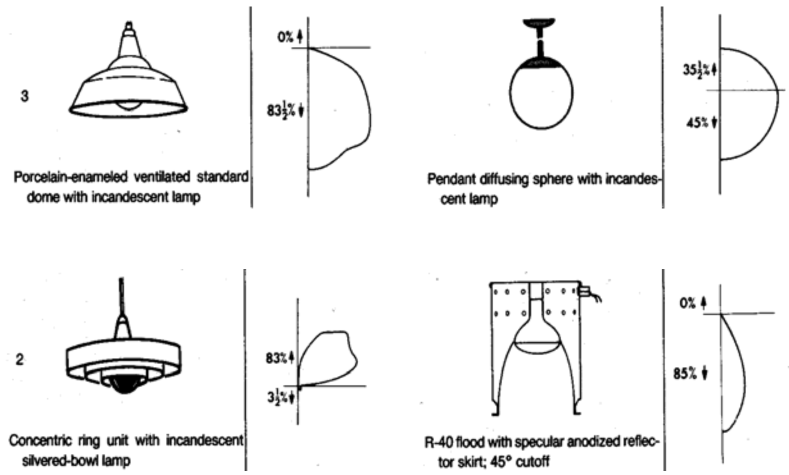


$$I(\ )\quad \cos^s \qquad (\vec{\ }\ \ \hat{\mathbf{A}})^s$$

$$\Phi = \int_0^{2\pi}\int_0^1 I(\omega)\, d\cos\theta\, d\varphi = 2\pi\int_0^1 \cos^s\theta\, d\cos\theta = \frac{2\pi}{s+1}$$

$$I(\omega) = \Phi\,\frac{s+1}{2\pi}\cos^s\theta$$

Light Source Goniometric Diagrams



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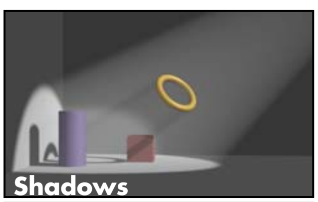
PIXAR Light Source




```
UberLight( )
{
  Clip to near/far planes
  Clip to shape boundary
  foreach superelliptical blocker
      atten *= …
  foreach cookie texture
      atten *= …
  foreach slide texture
      color *= …
  foreach noise texture
      atten, color *= …
  foreach shadow map
      atten, color *= …
  Calculate intensity fall-off
  Calculate beam distribution
}
```

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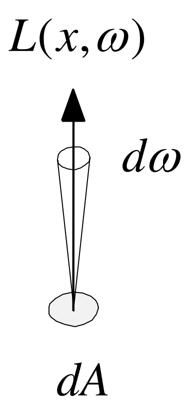
Radiance

Radiance

<u>Definition</u>: The *surface radiance* (*luminance*) is the intensity per unit area leaving a surface



$$L(x, \;) \quad \frac{dI(x, \;)}{dA}$$

$$\frac{d^2 \;\; (x, \;)}{d \;\; dA}$$

$$\frac{W}{sr\,m^2} \quad \frac{cd}{m^2} \quad \frac{lm}{sr\,m^2} \quad nit$$

Typical Values of Luminance [cd/m²]

Surface of the sun	2,000,000,000 nit
Sunlight clouds	30,000
Clear day	3,000
Overcast day	300
Moon	0.03

Radiant Exitance (Radiosity)

Radiant Exitance

<u>Definition</u>: The *radiant* (*luminous*) *exitance* is the energy per unit area leaving a surface.

$$M(x) \equiv \frac{d\Phi_o}{dA}$$

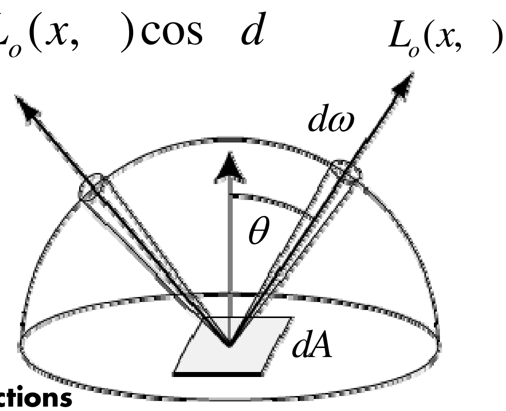
$$\left[\frac{W}{m^2}\right] \left[\frac{lm}{m^2} = lux\right]$$

In computer graphics, this quantity is often referred to as the *radiosity (B)*

Area Light Source

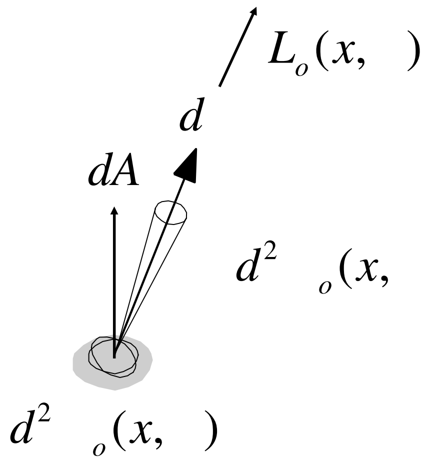
$$d^2 \quad _o(x, \quad) \qquad L_o(x, \quad)\cos \quad dAd$$

$$\frac{d^2 \quad _o(x, \quad)}{dA} \qquad L_o(x, \quad)\cos \quad d$$



Same *dA* for all directions

Directional Power Leaving a Surface

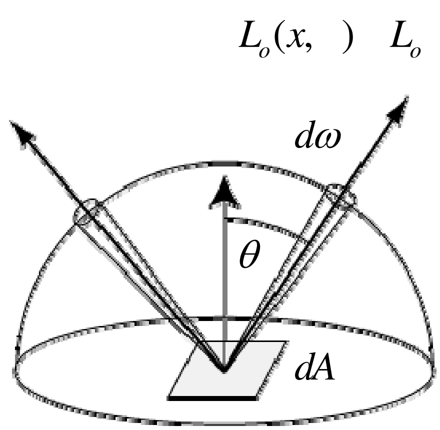


$$d^2 \ {}_o(x, \ ) \quad L_o(x, \ )\cos \ dAd$$

Uniform Diffuse Emitter

$$M \quad \int_{H^2} L_o \cos \ d$$

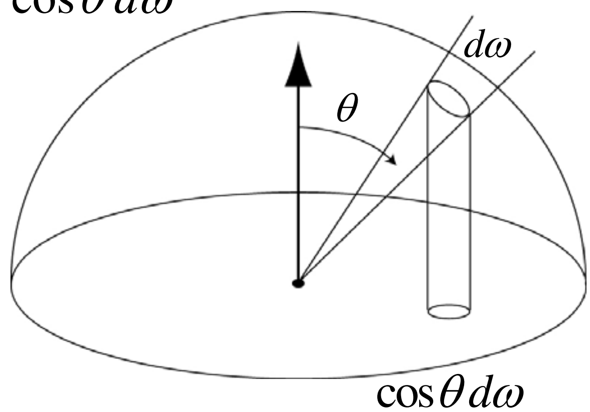
$$L_o \int_{H^2} \cos \ d$$



H^2 **Hemisphere**

Projected Solid Angle

$$\tilde{\Omega} \equiv \int_{\Omega} \cos\theta \, d\omega$$



$$\tilde{\ } \quad \quad \cos \quad d$$

H^2

Uniform Diffuse Emitter

$$M \quad \quad L_o \cos \quad d$$

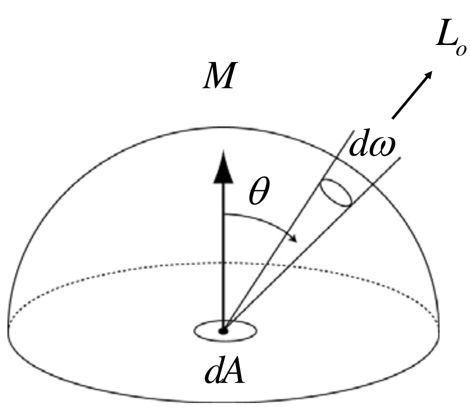
H^2

$$L_o \quad \cos \quad d \qquad \qquad M$$

H^2

$$L_o$$

$$L_o \quad \frac{M}{\ }$$



Irradiance

Irradiance

<u>Definition</u>: The *irradiance* (*illuminance*) is the power per unit area incident on a surface.

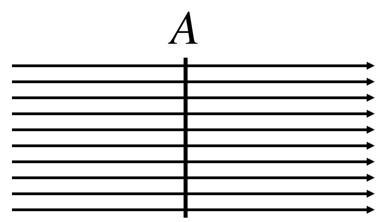
$$E(x) \quad \frac{d \quad _i}{dA}$$

$$\left[\frac{W}{m^2}\right] \left[\frac{lm}{m^2} = lux\right]$$

Sometimes referred to as the radiant (luminous) incidence.

Lambert's Cosine Law

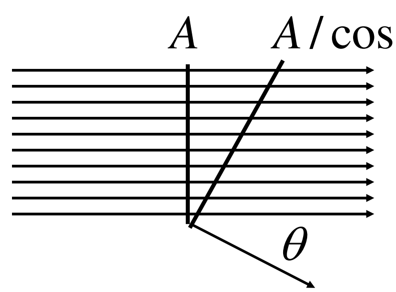
$$\Phi = EA$$



$$E = \frac{\Phi}{A}$$

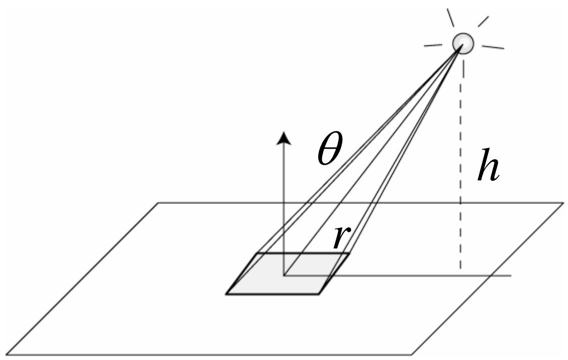
Lambert's Cosine Law

Φ



$$E = \frac{\Phi}{A/\cos\theta} = \frac{\Phi}{A}\cos\theta$$

Irradiance: Isotropic Point Source



$$I = \frac{\Phi}{4\pi}$$

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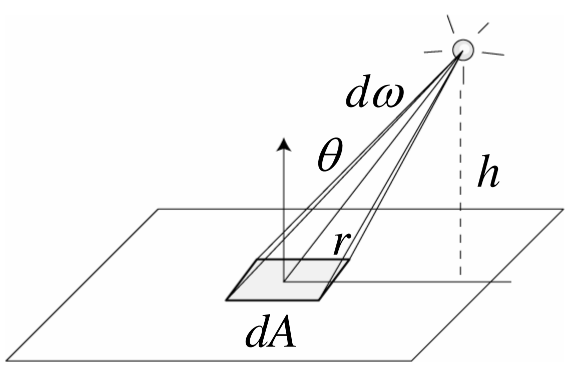
Irradiance: Isotropic Point Source



$$I = \frac{\Phi}{4\pi}$$

$$d\Phi = I\, d\omega$$

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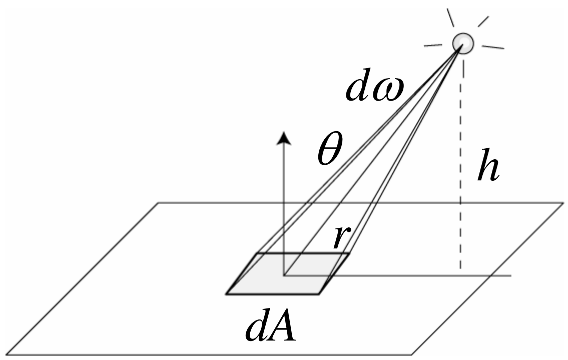
Irradiance: Isotropic Point Source



$$I = \frac{\Phi}{4\pi}$$

$$d\omega = \frac{\cos\theta}{r^2} dA$$

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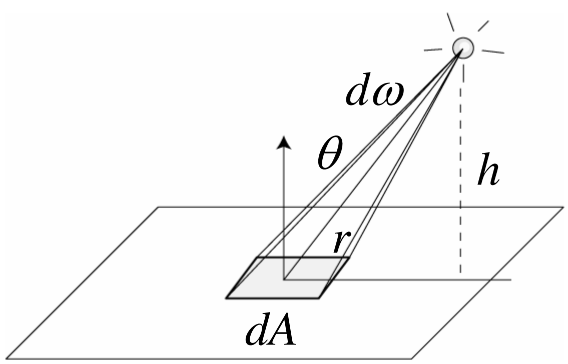
Irradiance: Isotropic Point Source



$$I = \frac{\Phi}{4\pi}$$

$$I\, d\omega = \frac{\Phi}{4\pi} \frac{\cos\theta}{r^2} dA$$

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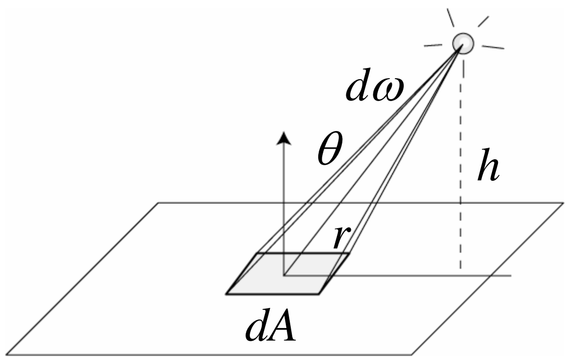
Irradiance: Isotropic Point Source



$$I = \frac{\Phi}{4\pi}$$

$$I\,d\omega = \frac{\Phi}{4\pi}\frac{\cos\theta}{r^2}\,dA = E\,dA$$

$$E = \frac{\Phi}{4\pi}\frac{\cos\theta}{r^2}$$

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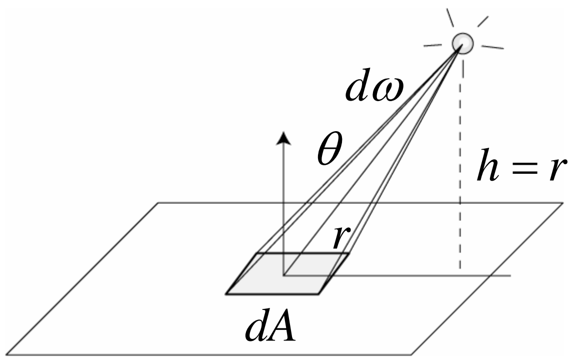
Irradiance: Isotropic Point Source



$$I = \frac{\Phi}{4\pi}$$

$$h = r\cos\theta$$

$$E = \frac{\Phi}{4\pi}\frac{\cos\theta}{r^2} = \frac{\Phi}{4\pi}\frac{\cos^3\theta}{h^2}$$

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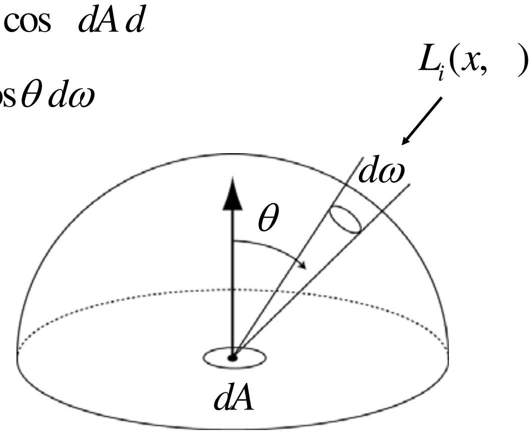
Typical Values of Illuminance [lm/m²]

Sunlight plus skylight	100,000 lux
Sunlight plus skylight (overcast)	10,000
Interior near window (daylight)	1,000
Artificial light (minimum)	100
Moonlight (full)	0.02
Starlight	0.0003

Irradiance from the Environment

$$d^2 \quad _i(x, \quad) \quad L_i(x, \quad)\cos \quad dA\, d$$

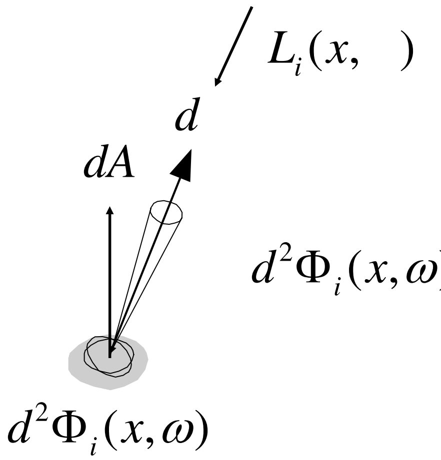
$$dE(x,\omega) = L_i(x,\omega)\cos\theta\, d\omega$$



Light meter

$$E(x) = \int_{H^2} L_i(x,\omega)\cos\theta\, d\omega$$

Directional Power Arriving at a Surface



$$d^2\Phi_i(x,\omega) = L_i(x,\omega)\cos\theta dA d\omega$$

The Sky Radiance Distribution

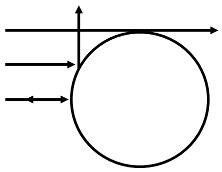
Plate 5-16. Fisheye view of clear sky at the South Pole. (Photographed by the author)

Plate 5-17. View of slightly hazy sky in Wisconsin. (Photographed by the author)

From Greenler, Rainbows, halos and glories

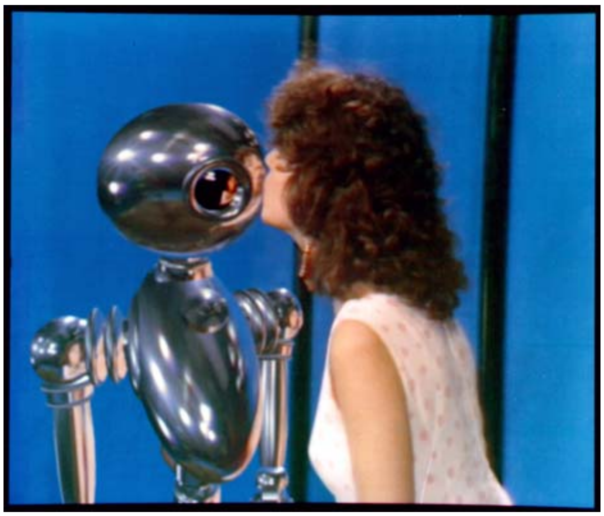
Gazing Ball ⇒ Environment Maps

Miller and Hoffman, 1984



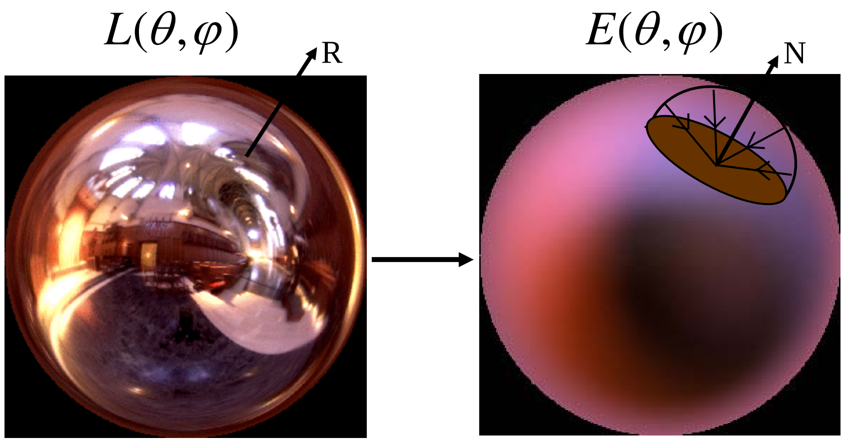
- Photograph of mirror ball
- Maps all spherical directions to a to circle
- Reflection direction indexed by normal
- Resolution function of orientation

Environment Maps



Interface, Chou and Williams (ca. 1985)

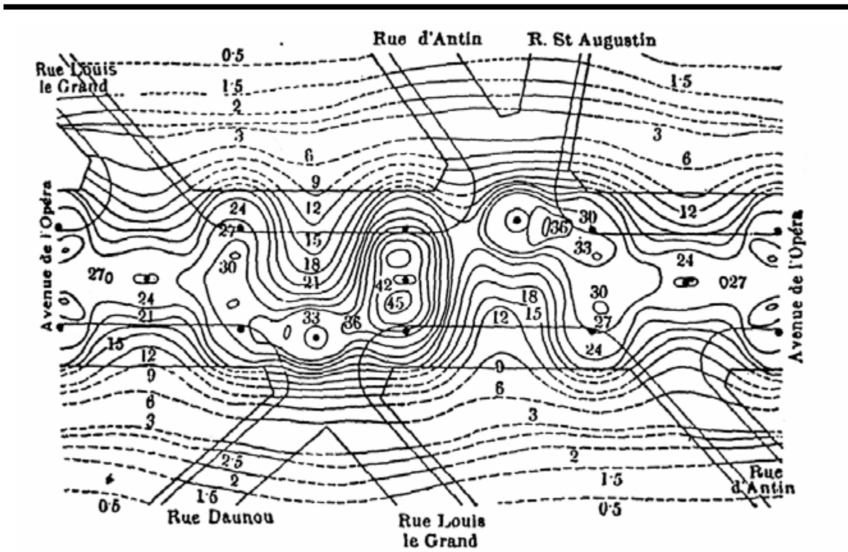
Irradiance Environment Maps



Radiance Environment Map

Irradiance Environment Map

Irradiance Map or Light Map



Isolux contours

Radiometry and Photometry Summary

Radiometric and Photometric Terms

Physics	Radiometry	Photometry
Energy	Radiant Energy	Luminous Energy
Flux (Power)	Radiant Power	Luminous Power
Flux Density	Irradiance Radiosity	Illuminance Luminosity
Angular Flux Density	Radiance	Luminance
Intensity	Radiant Intensity	Luminous Intensity

Photometric Units

Photometry	Units		
	MKS	CGS	British
Luminous Energy	Talbot		
Luminous Power	Lumen		
Illuminance Luminosity	Lux	Phot	Footcandle
Luminance	Nit Apostilb, Blondel	Stilb Lambert	Footlambert
Luminous Intensity	Candela (Candle, Candlepower, Carcel, Hefner)		

"Thus one nit is one lux per steradian is one candela per square meter is one lumen per square meter per steradian. Got it?", *James Kajiya*

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